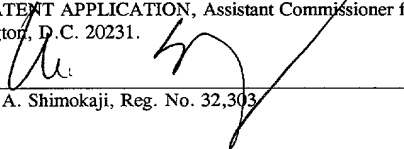


"Express Mail" label number EL887875069US

Date of deposit 2/6/02

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Michael A. Shimokaji, Reg. No. 32,303

PATENT
091-0108

HIGH SPEED QPSK MMIC AND QAM MODULATOR

BACKGROUND OF THE INVENTION

5 [001] The present invention generally relates to high frequency, high data rate wireless telecommunication systems and, more particularly, to band efficient modulation for quadrature phase shift keying (QPSK) and quadrature amplitude modulation (QAM) using monolithic microwave integrated circuits (MMIC).

10 [002] Capability of current communication systems is limited due to smaller channel bandwidth allocations, typically less than 100 MHz (mega Hertz, or million cycles per second), available in the FCC allocated frequency bands in the range of 1 to 40 giga Hertz (GHz). One way for current systems to achieve higher data rates within these bands, is to use modulation schemes which are more bandwidth efficient, but achieving more bandwidth-efficient modulation
15 presents rigorous technical challenges and typically requires more complex and expensive hardware.

[003] Conventional modulation systems consist of a modulator operated at an intermediate frequency (IF) and a number of filters, amplifiers and mixers that upconvert the modulated signal to the transmit frequency, also called the carrier
20 frequency. The demand for higher speed data transmission imposes increasingly stringent requirements on the modulators in these systems, as data rates approach the maximum bandwidth capabilities of these circuits. At multi-giga bit per second (Gbps) data rates, these modulator circuits become impractical as the bandwidth required for the high, multi-Gbps, data rate
25 becomes very wide relative to the intermediate frequency, referred to as relative bandwidth requirement, and exceeds the technology limitations of the modulator

circuit.

5 [004] Conventional modulation systems may address the relative bandwidth requirement by upgrading to newer and faster transistor technology, such as silicon-germanium, or SiGe, heterojunction transistor technology. The relatively
10 extensive hardware requirement for conventional modulation systems, however, makes upgrading the hardware relatively expensive. Another approach is to use digital modulation to enhance spectrum, i.e., bandwidth, efficiency. While digital techniques are generally desirable, a drawback to the digital modulation approach is the dependency on technological development of state-of-the-art
15 processes. This dependency becomes more critical when pushing the performance capabilities of new processes. In business applications, it may be difficult and costly to qualify new processes, especially where high reliability is a prime concern.

20 [005] MMICs have become an important advancement in the communications field. MMICs are low cost, high bandwidth circuit devices that operate at microwave and millimeter wave frequencies. MMIC's are analog circuits which downconvert a modulated signal to a baseband signal or upconvert the baseband signal to a microwave signal. One way to generate a high data rate signal is to directly modulate the microwave carrier at the high data rates. This
25 direct modulation scheme reduces physical size and cost of the communications system by eliminating much of the hardware previously needed in such systems. A major technical challenge in this type of modulation, however, is achieving low amplitude and phase error over the wide bandwidth requirement.

30 [006] Direct carrier modulation may use mature microwave device technology such as GaAs, and may also apply digital modulation techniques such as QPSK. An example of QPSK modulation is illustrated by the block diagram of Figure 1, where two-bit data word 102 and carrier 104 are input to phase modulator 100, which outputs QPSK modulated carrier 106 corresponding to a signal, S, of the form:

$$S(t)=A \cos(\omega_s t - \theta + \psi) \quad (1)$$

where A is the carrier amplitude constant and ψ is the phase constant. There are four possible values for two-bit data word 102. Phase modulator 100 maps each of the four possible values for two-bit data word 102 to a distinct value of the phase angle θ .

[007] The QPSK modulated carrier 106 output from phase modulator 100 may be represented on a phase diagram such as phase diagram 200 seen in Figure 2. Phase diagram 200 shows that phase angle θ will take on the form of one of four phases separated by 90 degrees. As shown in Figure 2, each of the four possible values of two-bit data word 102 is represented by a symbol 202, which is a point, or vector, s_1 , s_2 , s_3 or s_4 , in the phase plane of phase diagram 200. Two bits of information, or one symbol, is sent every word time corresponding to one of the four vectors, or symbols, in phase diagram 200.

[008] The symbols of a QPSK signals may also be conceptualized as two pairs of a bi-orthogonal set. Figure 3 shows a common implementation, using that concept, of QPSK modulator 300 employing orthogonal bi-phase shift keying (BPSK) modulators 310 and 320. The circuit of QPSK modulator 300 shown in Figure 3 uses double-balanced mixers for BPSK modulators 310 and 320. As seen in Figure 3, two-bit data word 302 is extracted from bit sequences 303 and 305. Bit sequence 303 and carrier 314 are input to BPSK modulator 310, which outputs BPSK modulated signal 316. Bit sequence 305 and carrier 324 are input to BPSK modulator 320, which outputs BPSK modulated signal 326. BPSK modulated signals 316 and 326 are added by summer 330 and output as QPSK modulated carrier 336 corresponding to a signal, S, of the form:

$$S(t)=A \cos(\omega_s t - \theta + \psi) \quad (2)$$

where A is the carrier amplitude constant and ψ is the phase constant. There are four possible values for two-bit data word 302 each of which is mapped to a distinct value of the phase angle θ . Because carriers 314 and 316 differ in phase by 90 degrees, phase angle θ will take on one of four phase values separated by 90 degrees, as shown in Figure 2, with each of the four possible

values of two-bit data word 302 represented by a symbol 202, which is a vector, s_1 , s_2 , s_3 or s_4 , in the phase plane of phase diagram 200.

[009] Figure 4 shows a basic MMIC implementation of QPSK modulator 400 using a number of 90 degree Lange couplers 402, 404, 406, and 408.

5 Conventional MMIC implementation of QPSK modulator 400 has carrier input 410 entering QPSK modulator 400 and then split into two orthogonal components 412 and 414 by use of Lange coupler 402. Orthogonal components 412 and 414 then pass into two variable bi-phase modulators 404 and 406, which each include another Lange coupler. Bi-phase modulators 404 and 406 split the signal again before the signal goes into variable reflection loads 416, 418, 420, and 422. These complex circuits have been popular as analog modulators, or as vector modulators, where both amplitude and phase are varied. Normally, 90 degree hybrids or Lange couplers are used. The added complexity of these circuit designs and the technical difficulties they present in achieving the low amplitude and phase error over the wide bandwidth requirement needed for high data rate operation, however, has largely limited them to Mbps data rates, where the relative bandwidth requirement is reduced because the bandwidth required for the lower, Mbps, data rate is narrow enough relative to the higher intermediate or carrier frequency.

20 **[0010]** Figure 5 shows how two QPSK modulation systems 510 and 520 may be combined in a QAM modulation system 500 to achieve a 16 QAM signal 536. An RF or IF carrier is provided by local oscillator 504 using timing reference 501, as known in the art. The RF or IF carrier is split into carriers 514 and 524, and each is fed into QPSK modulation systems 510 and 520, respectively.

25 Two-bit data word 512, which includes bits b_0 and b_1 as shown in Figure 5, and carrier 514 are input to QPSK modulation system 510. QPSK modulation system 510 outputs QPSK modulated carrier 516 corresponding to a signal which may be represented, as described above in connection with Figure 2, by vectors 616 on phase diagram 610 shown in Figure 6. Similarly, two-bit data

30 word 522, which includes bits b_2 and b_3 as shown in Figure 5, and carrier 524

are input to QPSK modulation system 520. QPSK modulation system 520 outputs a QPSK modulated carrier 526, which travels through attenuator 527. Attenuator 527 lowers the amplitude of QPSK modulated carrier 526. The attenuated QPSK modulated carrier 526 corresponds to a signal which may be represented, as described above in connection with Figure 2, by vectors 626 on phase diagram 620 shown in Figure 6.

[0011] As seen in Figure 5, the two QPSK modulated carriers 516 and 526 are added by summer 530 and output as QAM modulated carrier 536 corresponding to a signal which may be represented, as described above in connection with Figure 2, by vectors 636 on phase diagram 630 shown in Figure 6. The addition of QPSK modulated carriers 516 and 526 is indicated in Figure 6 by plus sign 632 and equal sign 634 representing addition of phase diagrams 610 and 620 corresponding to QPSK modulated carriers 516 and 526, respectively. Because each vector 616 and 626 represents a signal, addition of the phase diagrams is accomplished by adding each possible pair of vectors 616 and 626 to produce a vector or symbol 636 in phase diagram 630. The configuration formed by symbols 636 is referred to as a 16 QAM constellation. The vectors 616 are also shown in phase diagram 630 to provide a size orientation for the purposes of illustration only, but do not form part of the 16 QAM constellation illustrated in phase diagram 630. Each symbol 636 represents a pair of two-bit data words 512 and 522, which may be viewed as a four-bit data word, b_0, b_1, b_2, b_3 . Each four-bit data word has 16 possible values each of which is mapped by QAM modulation system 500 to one distinct symbol 636 of the 16 symbols 636.

[0012] Physical limitations and variances in the circuits used to implement QAM modulation system 500 cause variance, or inexactitude, in the amplitudes and phases of symbols 636 during transmission of the QAM modulated signal. The variances may cause some of the symbols 636 to occasionally be transmitted closer together in phase diagram 630. If the variances, or imperfections, are too great, the receiver may not be able to reliably provide resolution of the

symbols to permit faithful demodulation of the QAM modulated signal at the receiver. Imperfections that limit the effectiveness of QAM modulation systems, may be reduced by achieving low amplitude and phase error over the channel bandwidth. The technical difficulties in achieving low amplitude and phase error
5 over the channel bandwidth have restricted the use of QAM modulation systems to lower frequencies and narrower bandwidths than is desirable.

[0013] As can be seen, there is a need for direct modulation in communication systems that reduces the relative bandwidth requirement, thus allowing higher data rates relative to the carrier frequency. Moreover, there is a need for
10 modulation in communication systems that use MMIC to improve amplitude and phase balance, and achieve operation at higher frequencies where wider channel bandwidth allocations are potentially available.

SUMMARY OF THE INVENTION

[0014] The present invention provides direct modulation in wireless telecommunication systems that reduces the relative bandwidth requirement, thus allowing higher data rates relative to the carrier frequency. Moreover, the present invention provides modulation in wireless telecommunication systems
20 that use MMIC to improve amplitude and phase balance to achieve operation at higher frequencies where wider channel bandwidth allocations are potentially available.

[0015] In one aspect of the present invention, in a system for modulating an RF carrier, the RF carrier is fed through a lowpass filter and phase shifted approximately -90 degrees. The RF carrier is also fed through a high pass filter and phase shifted approximately +90 degrees. A switch connected to the output of the lowpass filter and connected to the output of the highpass filter, selects and outputs either the -90 degree phase shifted carrier output from the lowpass filter or the +90 degree phase shifted carrier output from the highpass
25 filter depending on a switching state determined by data bit information received
30

at a data port to produce a BPSK modulated RF carrier.

[0016] In another aspect of the present invention, in a system for modulating an RF carrier, the RF carrier is fed through a lowpass filter and phase shifted approximately -45 degrees. The RF carrier is also fed through a high pass filter and phase shifted approximately +45 degrees. A BPSK modulator using lowpass and highpass filters to phase shift the RF carrier approximately +90 or -90 degrees and a switch to select the output determined by data bit information received at a data port, as described above, is connected to the output of the lowpass filter. Another BPSK modulator, of substantially identical configuration, using lowpass and highpass filters to phase shift the RF carrier approximately +90 or -90 degrees and a switch to select the output determined by data bit information received at a data port, as described above, is connected to the output of the highpass filter. A power divider connected to the output of the first BPSK modulator and connected to the output of the second BPSK modulator is configured to produce as output a QPSK modulated RF carrier, which is the vector sum of the output of the first BPSK modulator and the output of the second BPSK modulator.

[0017] In still another aspect of the present invention, in a system for modulating an RF carrier, the RF carrier is fed through two substantially identically configured QPSK modulators using lowpass and highpass filters, switches, and power dividers to phase shift the RF carrier approximately +45, -45, +135 or -135 degrees, as described above. An attenuator has its input connected to the output of the second QPSK modulator. A vector summer is connected to the output of the first QPSK modulator and is also connected to the output of the attenuator. The vector summer is configured to produce as output a QAM modulated RF carrier, which is the vector sum of the output of the first QPSK modulator and the attenuated output of the second QPSK modulator from the attenuator.

[0018] In a further aspect of the present invention, a method for modulating an RF carrier includes steps of passing the RF carrier through a lowpass filter, to

produce a first phase shifted carrier output; and also passing the RF carrier through a highpass filter to produce a second phase shifted carrier output; providing data bit information to a data port; and employing a switch connected to the output of the lowpass filter and connected to the output of the highpass filter to select and output either the first phase shifted carrier output from the lowpass filter or the second phase shifted carrier output from the highpass filter depending on a switching state determined by the data bit information provided to the data port.

[0019] These and other features, aspects and advantages of the present invention will become better understood with reference to the following drawings, description and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020] Figure 1 is a block diagram for a typical implementation of quadrature phase shift keying (QPSK) modulation;

[0021] Figure 2 is a phase diagram for a typical implementation of QPSK modulation;

[0022] Figure 3 is a block diagram for QPSK modulation as typically implemented using bi-phase shift keying (BPSK);

[0023] Figure 4 is a block diagram for QPSK modulation as typically implemented using monolithic microwave integrated circuits (MMIC);

[0024] Figure 5 is a block diagram of quadrature amplitude modulation (QAM) as typically implemented using QPSK;

[0025] Figure 6 is a group of phase diagrams illustrating the implementation of QAM as typically implemented using QPSK;

[0026] Figure 7 is a block diagram of a filter network implementation of BPSK in MMIC, according to an embodiment of the present invention;

[0027] Figure 8 is a block diagram of a filter network implementation of QPSK modulation implemented using BPSK, according to an embodiment of the

present invention; and

[0028] Figure 9 is a block diagram of QAM implemented using QPSK, according to an embodiment of the present invention.

5

DETAILED DESCRIPTION OF THE INVENTION

[0029] The following detailed description is of the best currently contemplated modes of carrying out the invention. The description is not to be taken in a limiting sense, but is made merely for the purpose of illustrating the general principles of the invention, since the scope of the invention is best defined by

10 the appended claims.

[0030] The present invention provides direct modulation in wireless telecommunication systems that reduce the relative bandwidth requirement, thus allowing higher data rates relative to the carrier frequency. The present invention may use monolithic microwave integrated circuits (MMIC) or application specific integrated circuits (ASIC) to directly modulate a microwave carrier at high data rates in a quadrature phase shift keying (QPSK) format or a quadrature amplitude modulation (QAM) format. The method of direct modulation in an embodiment of the present invention increases data rate and

15 provides a better bandwidth efficient modulation scheme for transmission and receiving of data, rendering an economic advantage where spectrum allocations are limited. In one embodiment, the present invention reduces required hardware and reduces operating costs.

20

[0031] The present invention also provides modulation in wireless telecommunication systems that achieve low amplitude and phase error -- or imbalance -- over a wide bandwidth, thus lowering inter-symbol interference. In one embodiment, a modulation system exhibits an amplitude and phase imbalance of less than plus or minus 0.3 dB and 2 degrees respectively over a 6 GHz bandwidth. In one embodiment, a modulation system is capable of

25 delivering approximately 6 Gbps of data using an analog 16 QAM modulation

30

scheme. Unlike prior art QAM systems, which are unable to achieve comparable levels of performance, the analog 16 QAM modulation scheme may be implemented as a direct result of the benefits of a QPSK MMIC implemented to operate at high switching speeds with improved vector, i.e., amplitude and phase, performance.

[0032] Moreover, the present invention provides modulation in wireless telecommunication systems that use MMIC to improve amplitude and phase balance and achieve operation at higher frequencies where wider channel bandwidth allocations are potentially available. In one embodiment, an approach is taken to implementing QPSK modulation in MMIC that differs from standard QPSK modulation found in the prior art. The approach, in one embodiment, puts a filter network into place to significantly improve over the prior art on the amplitude and phase balance. The MMIC technology integrated into a QPSK modulation scheme differs from prior art by using a filter network to achieve higher switching speed -- which translates into higher data rates -- and improved amplitude and phase balance.

[0033] Direct carrier modulators have been constructed in hybrid MIC technology, but at low data rates. High data rate modulation necessitates an MMIC approach, where device and component matching, and circuit symmetry are more tightly controlled. This is important in maintaining the required amplitude and phase balance over wide bandwidths.

[0034] In one embodiment, a k-band QPSK MMIC modulation system has been fabricated in a 0.25 micrometer gallium arsenide (GaAs) pseudomorphic high electron mobility transistor (PHEMT) process, and has been developed and tested up to data rates of approximately 6 Gbps. The MMIC has been incorporated into multi-Gbps modulation systems demonstrating excellent bit error rate (BER) performance. Direct digital modulation of a microwave carrier in a GaAs MMIC reduces the hardware complexity and size of traditional modulation systems (modulator, filters, upconverter). The high degree of device and component repeatability and circuit symmetry that is achieved in a GaAs

MMIC yields low amplitude and phase imbalance over a wide -- greater than 6 GHz -- bandwidth, thus enabling low-distortion (low BER), high data rate modulation capability.

5 [0035] The present invention differs from the prior art in the use of filters integrated into a general MMIC design. The present invention also differs from the prior art in the specific placement of these filters to give the correct vector sum. The present invention further differs from the prior art in the implementation using highpass filters and lowpass filters to separate two signals in an MMIC by 90 degrees. The present invention also differs from the prior art
10 by then sending each signal through identical BPSK modulators with lowpass and highpass filters.

[0036] Referring now to Figure 7, bi-phase shift keying (BPSK) modulator 700 is illustrated according to one embodiment. BPSK modulator 700 may be implemented in MMIC using a series of filter networks to accomplish the desired
15 phase shifts and to achieve the high frequency operation, amplitude and phase balance of BPSK modulator 700. The function of BPSK modulator 700 is to phase shift a carrier 702, depending on data bit information at data ports 704 and 705, to one of two vector states, as generally described above. The vector representation may be illustrated using a phase diagram similar to phase
20 diagram 200 shown in Figure 2.

[0037] Continuing with Figure 7, carrier 702, which may be an RF carrier at a frequency of approximately 19.6 GHz, is input to power divider 706 of BPSK modulator 700. Power divider 706 splits carrier 702 into two equal amplitude signals and feeds carrier 702 into lowpass filter 708 and highpass filter 710.
25 Lowpass filter 708 and highpass filter 710 may be implemented in MMIC as similar filters to achieve the precision phase and amplitude balance of BPSK modulator 700. As seen in Figure 7, lowpass filter 708 introduces a phase shift of -90 degrees into carrier 702 and highpass filter 710 introduces a phase shift of +90 degrees into carrier 702. The -90 degree phase shifted carrier 712 or the
30 +90 degree phase shifted carrier 714 is selected by switch 716 depending on

the switching states determined by the data bit information at the I and I-bar data ports 704 and 705. The data bit information at the I and I-bar data ports 704 and 705 may be fed through identical 20 GHz notch filters 718 and 720 to switch 716, as shown in Figure 7. The notch filters are centered about the
5 frequency of carrier 702, i.e. approximately 19.6 GHz, to prevent direct interference between the data input sequences and carrier 702. Switch 716 outputs bi-phased signal 722 at -90 or +90 degrees, which is the BPSK output of BPSK modulator 700, as seen in Figure 7.

[0038] Referring now to Figure 8, QPSK modulator 800 illustrates an example of
10 combining two BPSK modulators 830 and 840, as described above in relation to Figure 7, to provide QPSK modulation in accordance with one embodiment. QPSK modulator 800 may be implemented in MMIC using a series of filter networks to accomplish the desired phase shifts and to achieve the high frequency operation, amplitude and phase balance of QPSK modulator 800.
15 The function of QPSK modulator 800 is to phase shift a carrier 802, depending on data bit information at data ports 834, 835, 844, and 845, to one of four orthogonal vector states, as generally described above. The vector representation may be illustrated using a phase diagram similar to phase diagram 200 shown in Figure 2.

[0039] Continuing with Figure 8, carrier 802, which may be an RF carrier at a
20 frequency of 19.6 GHz, is input to power divider 806 of QPSK modulator 800. Power divider 806 splits carrier 802 into two equal amplitude signals and feeds carrier 802 into lowpass filter 808 and highpass filter 810. Lowpass filter 808 and highpass filter 810 may be implemented in MMIC as similar filters to
25 achieve the precision phase and amplitude balance of QPSK modulator 800. As seen in Figure 8, lowpass filter 808 introduces a phase shift of -45 degrees into carrier 802 and highpass filter 810 introduces a phase shift of +45 degrees into carrier 802 resulting in two signals 831 and 841 spaced 90 degrees apart (in quadrature). Each signal 831 and 841 then passes through identical BPSK
30 modulators 830 and 840, which may be identically configured on an MMIC or

ASIC chip to achieve the precision phase and amplitude balance of QPSK modulator 800. BPSK modulators 830 and 840, through similar lowpass and highpass filters, as described above in connection with Figure 7, phase shift the signals either -90 or +90 degrees depending on the switching states. The
5 switching states are determined by the data bit information at the I and I-bar data ports 834, 835 and the Q and Q-bar data ports 844 and 845. The data bit information at the I, I-bar, Q, and Q-bar data ports 834, 835, 844, and 845 may be fed through identical notch filters, centered about the frequency of carrier 802, approximately 20 GHz in the examples used to illustrate the embodiments
10 described here, and as described above in relation to Figure 7, to prevent direct interference between the I and Q data input sequences at data ports 834, 835, 844, and 845 and carrier 802.

[0040] BPSK modulators 830 and 840 output two bi-phased signals 836 and 846 in quadrature, signal 846 at -45 or +135 degrees, and signal 836 at -135 or
15 +45 degrees relative phase. Signals 836 and 846 may be fed to power divider 850. The vector sum 856 of the two signals 836 and 846 produced by power divider 850 is the final QPSK output of QPSK modulator 800.

[0041] Figure 9 shows how two QPSK modulation systems 910 and 920, as described above in connection with Figure 8, may be combined in a QAM
20 modulation system 900 to achieve a 16 QAM signal 936 according to one embodiment. QAM modulation system 900 may integrate QPSK MMIC filter networks, according to an embodiment as described above, to achieve amplitude and phase balance. An RF or IF carrier, which may be an RF carrier at a frequency of 19.6 GHz, for example, is provided by local oscillator 904
25 using timing reference 901, as known in the art. The RF or IF carrier is split into carriers 914 and 924, and each is fed into QPSK modulation systems 910 and 920, respectively, both of which may be implemented on a single MMIC or ASIC using filter networks to achieve amplitude and phase balance in accordance with an embodiment, as described above and as seen in Figure 8. Two-bit data
30 word 912, which includes bits b_0 and b_1 as shown in Figure 9, and carrier 914

are input to QPSK modulation system 910. Bits b_0 and b_1 , for example, may correspond to the I and Q data input sequences at data ports 834, 835, 844, and 845 of a first QPSK modulator 800 as described above. QPSK modulation system 910 outputs QPSK modulated carrier 916 corresponding to a signal which may be represented by vectors 616 on phase diagram 610 shown in Figure 6.

[0042] Similarly, two-bit data word 922, which includes bits b_2 and b_3 as shown in Figure 9, and carrier 924 are input to QPSK modulation system 920. Bits b_2 and b_3 , for example, may correspond to the I and Q data input sequences at data ports 834, 835, 844, and 845 of a second QPSK modulator 800 as described above. QPSK modulation system 920 outputs a QPSK modulated carrier 926, which travels through attenuator 927. Attenuator 927 lowers the amplitude of QPSK modulated carrier 926. QAM modulation system 900 may further include an automatic gain and phase control 928 to compensate for the many distortions that occur throughout the system. Automatic gain and phase control 928 varies the attenuator value based on how the distortions affect the output signal, QPSK modulated carrier 926. The attenuated QPSK modulated carrier 926 corresponds to a signal which may be represented by vectors 626 on phase diagram 620 shown in Figure 6.

[0043] As seen in Figure 9, the two QPSK modulated carriers 916 and 926 are added by summer 930 and output as QAM modulated carrier 936 corresponding to a signal which may be represented by vectors 636 on phase diagram 630 shown in Figure 6. The vectors 616 are also shown in phase diagram 630 to provide a size orientation for the purposes of illustration only, but do not form part of the 16 QAM constellation illustrated in phase diagram 630. Each symbol 636 represents a pair of two-bit data words 912 and 922, which may be viewed as a four-bit data word, b_0, b_1, b_2, b_3 . Each four-bit data word has 16 possible values, each of which is mapped by QAM modulation system 900 to one distinct symbol 636 of the 16 symbols 636.

[0044] Because of the superior amplitude and phase balance, i.e., reduced

amplitude and phase error, achieved by the implementation of QAM modulation system 900 in MMIC using filter networks according to an embodiment, inter-symbol interference is sufficiently reduced for QAM modulation system 900 to achieve the desirable high frequency and wide bandwidth communications described above.

[0045] It should be understood, of course, that the foregoing relates to preferred embodiments of the invention and that modifications may be made without departing from the spirit and scope of the invention as set forth in the following claims.